Eur Phys J C **34**, s01, s433–s442 (2004)
Digital Object Identifier (DOI) 10.1140/epjcd/s2004-04-047-1

EPJ C direct
electronic only

LHC accelerator R&D and upgrade scenarios

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Received: 3 August 2003 / Accepted: 17 November 2003 /

Abstract. I report the results of a CERN task force set up to investigate a possible staged upgrade of the LHC and of its injectors, with a view to increasing the machine luminosity by an order of magnitude from the nominal $10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ to $10^{35}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. Scenarios for an LHC energy upgrade by nearly a factor two have also been considered. An interesting outcome of these discussions has been a novel approach to the optimization of the collider performance, compatible with the beam-beam limit for high intensity proton bunches or long 'super-bunches'. I also sketch a new design of the interaction regions, including an alternative beam crossing scheme. To put things in perspective, I first address LHC commissioning scenarios and challenges associated with machine protection and electron cloud effects. Finally I discuss further studies required for an LHC performance upgrade and outline an R&D programme.

1 Introduction

A CERN task force has been set up in July 2001 to investigate a possible staged upgrade of the LHC and of its injectors, compatible with established accelerator design criteria and fundamental limitations of the hardware subsystems, aiming at a target luminosity in proton operation of $10^{35}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ in each of the two high-luminosity experiments. Scenarios for an energy upgrade to $\sqrt{s} \simeq 25\,\mathrm{TeV}$ have also been explored. The resulting feasibility study has been published as a CERN LHC Project report [1]. A parallel task force has analysed the physics potential and experimental challenges of the LHC upgrade [2]. Machine upgrade scenarios and technological challenges associated with superconducting magnets have been further addressed in subsequent workshops [3], and the findings of the two CERN task forces have been presented at an ICFA Seminar in October 2002 [4] and later at an LHC experiments Committee [5]. The LHC performance upgrade is included in the recent initiative of the European Steering Group on Accelerator R&D [6] and in the US LHC Accelerator Research Program [7].

In their present configuration, the CMS and ATLAS detectors can accept a maximum luminosity of $3 \div 5 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. An increase in instantaneous luminosity may require positioning the low-β quadrupoles closer to the interaction point. If this were to be the scheme chosen, then a re-design of the calorimeters, muon detectors and radiation shielding in the forward region would probably be needed. Integrating the shielding with the calorimeters would be one option to provide a compact layout.

Upgrades in beam intensity and brilliance are a viable option for a staged increase of the LHC luminosity. The so-called ultimate bunch intensity of 1.7×10^{11} p/bunch corresponds to a luminosity of $2.3 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ and is compatible with the present beam dumping system. Further increases of the bunch intensity could still be tolerated accepting somewhat reduced safety margins or implementing moderate upgrades. Machine protection and collimation will be challenging, but it may be possible to reach a peak luminosity exceeding $3.5 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ without hardware modifications of the Interaction Regions (see Table 2). If nominal (ultimate) luminosity is reached by 2011, the radiation damage limit for IR quadrupoles, currently estimated to about $700\,\mathrm{fb}^{-1}$, is reached by 2017 (2013) [8].

To put things in perspective, I start in Sect. 2 by addressing LHC commissioning scenarios discussed at the LHC Performance Workshop in March 2003 [9], and challenges associated with machine protection and electron cloud effects. Then in Sect. 3 I outline luminosity optimization and in Sects. 4–6 LHC upgrade scenarios. Finally, in Sect. 7, I discuss further studies required for an LHC performance upgrade and outline an R&D programme.

2 LHC commissioning scenarios

LHC commissioning parameters will be constrained by several considerations. In particular, only 8 of the 20 LHC dump dilution kickers will be available during the first two years of operation. This limits the total beam intensity in each LHC ring to *one half* of its nominal value. Moreover, according to SPS experience and to electron cloud simulations [10], the initial LHC bunch intensity can reach and possibly exceed its nominal value for 75 ns bunch spacing, while it is limited to about *one third* of its nominal value for 25 ns bunch spacing. This limit can be overcome once a sufficient electron dose is accumulated on the vacuum

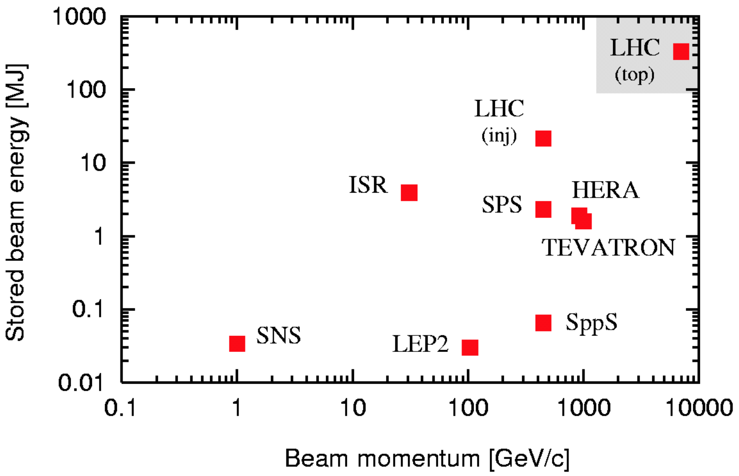

Fig. 1. Energy stored in the beam for different accelerators (courtesy R. Assmann). The energy stored in the nominal LHC beam at 7 TeV is 10000 times that in the LEP2 beam and 200 times that in the Tevatron beam. Machine protection and collimation at the LHC is challenging, since the transverse energy density is even a factor 1000 larger

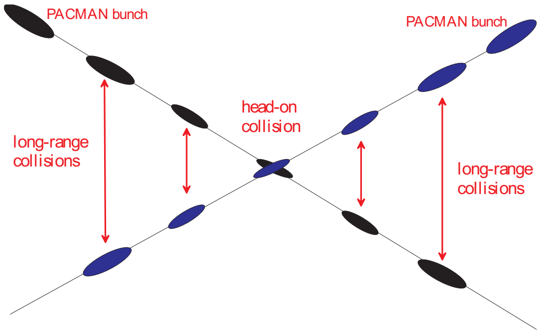

Fig. 2. Schematic of long range beam-beam collisions on either side of the main interaction point (courtesy F. Zimmermann)

chamber walls, either by dedicated scrubbing runs or during the first few weeks/months of the initial luminosity run.

In addition to such 'hard limits', it should be mentioned that machine protection and collimation favours initial operation with low beam power and low transverse beam density (see Fig. 1). Also emittance preservation from injection to physics conditions will require a learning curve. Therefore we prefer to assume a *nominal transverse emittance* even for reduced bunch intensity. Initial machine operation with relaxed parameters is strongly favoured; in particular a higher value of β^*, a reduced crossing angle, and fewer parasitic collisions will ensure a smooth LHC running in.

The transverse energy density of the LHC beams is proportional to the number of bunches n_b times the brilliance N_b/ε_n, times the square of the beam energy E

$$\rho_E = \frac{n_b N_b E}{2\pi\sigma_x\sigma_y} \sim n_b \frac{N_b}{\varepsilon_n} E^2 .$$

For nominal 25 ns bunch spacing and nominal energy, simple graphite collimators (or the necessary learning period to master machine collimation/protection) may limit

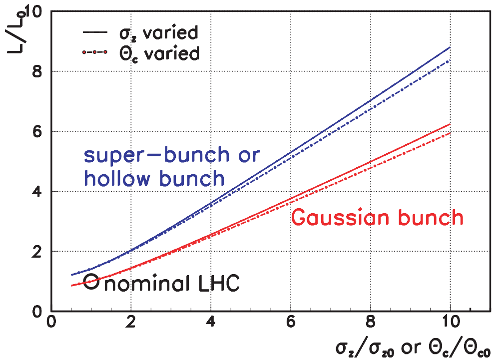

Fig. 3. Relative increase in LHC luminosity versus bunch length (or crossing angle) for Gaussian and flat (super-) bunches at constant beam-beam tune shift with alternating crossings in IP1 and IP5 [13]

the transverse energy density and thus the *brilliance* to about *one half* of its nominal value. Together with the relaxed emittance preservation during LHC commissioning, this rules out an initial luminosity run with 25 ns bunch spacing, reduced bunch intensity and lower transverse emittance, to reach the beam-beam limit and accumulate 10 fb^{-1} in 200 fills with relaxed β^* and a small crossing angle.

According to the above considerations, a list of possible LHC commissioning parameters for 75 ns and for 25 ns bunch spacing is presented in Table 1. The last column gives a list of slightly revised nominal parameters for 25 ns bunch spacing, taking into account a reduction of the available mechanical aperture associated with the installation of beam screens in the triplet magnets. After a learning period, required to master orbit control during β-squeeze, it may be possible to reach the 'old' nominal $\beta^* = 0.5$ m and to commission larger crossing angles.

3 LHC performance limitations and scaling laws

The LHC peak luminosity will be limited by the nonlinear beam-beam interaction. A design criterion for nominal LHC performance is that the total beam-beam tune spread induced by head-on and parasitic collisions in *all four IPs* should not exceed the value $\Delta Q_{\rm bb} \simeq 0.01$, so that the corresponding betatron 'tune footprint' can be accommodated in between resonances of order lower than or equal to 12.

Note that so-called 'Pacman bunches', near the edge of the bunch trains (see Fig. 2), experience different numbers of long range collisions and may have significantly different beam-beam footprints and closed orbits. The linear tune shift due to long range encounters cancels if half of the beam-beam crossings take place in the vertical and the other half in the horizontal plane. This is true even for Pacman bunches [11]. Therefore an additional design criterion to reach and exceed nominal LHC performance is to minimize the effect of long range encounters, by alternating horizontal-vertical crossing planes and by a sufficiently large crossing angle, corresponding to about $10\,\sigma$ beam separation at the parasitic collision points.

3.1 Luminosity optimization

The luminosity L for beams colliding with a total crossing angle $\theta_{\rm c}$ is reduced by a geometric factor F given by

$$L = \frac{N_{\rm b}^2 f_{\rm rep}}{4\pi\sigma^{*2}}\,F, \qquad F \simeq 1\Big/\sqrt{1+\left(\frac{\theta_{\rm c}\sigma_z}{2\sigma^*}\right)^2},$$

where $f_{\rm rep} = n_{\rm b} f_{\rm o}$ denotes the average bunch repetition frequency, σ_z the r.m.s. bunch length, and $\sigma^* = \sqrt{\varepsilon\beta^*}$ the r.m.s. transverse beam size at the IP ($\sigma^* \simeq 16\,\mu$m for nominal LHC parameters). The ratio $\theta_{\rm c}\sigma_z/\sigma^*$ is known as 'Piwinski parameter'. If the beam intensity is limited by effects other than the beam-beam interaction, the best strategy to maximize luminosity consists in operating the machine with short bunches and minimum crossing angle, compatible with adequate beam separation to reduce the effect of long range collisions.

The total linear tune shift for short bunches colliding with a crossing angle in alternating horizontal-vertical planes is also reduced by the same geometric factor F

$$\Delta Q_{\rm bb} = \xi_{\rm x} + \xi_{\rm y} = \frac{N_{\rm b} r_{\rm p}}{2\pi\varepsilon_{\rm n}}\,F,$$

where $r_{\rm p}$ denotes the classical proton radius, $\varepsilon_{\rm n} = \beta\gamma\varepsilon$ the normalised transverse emittance, and the ratio $N_{\rm b}/\varepsilon_{\rm n}$ is the brilliance. Therefore, if the bunch intensity is not limited by the injectors or by other effects in the LHC (*e.g.*, by the electron cloud build-up), it is possible to increase the luminosity without exceeding the beam-beam limit $\Delta Q_{\rm bb} \simeq 0.01$ by increasing the brilliance and the product of crossing angle times bunch length, as shown in Fig. 3. This alternative approach had not been considered in the original LHC design. It requires higher bunch intensities and is more challenging for machine protection, collimation, and beam dump. Expressing the beam-beam limited bunch intensity $N_{\rm b}$ in terms of the beam-beam tune shift $\Delta Q_{\rm bb}$, the corresponding peak luminosity is given by the approximate formula

$$L \simeq \gamma \Delta Q_{\rm bb}^2 \frac{\pi\varepsilon_{\rm n} f_{\rm rep}}{r_{\rm p}^2\beta^*}\sqrt{1+\left(\frac{\theta_{\rm c}\sigma_z}{2\sigma^*}\right)^2}.$$

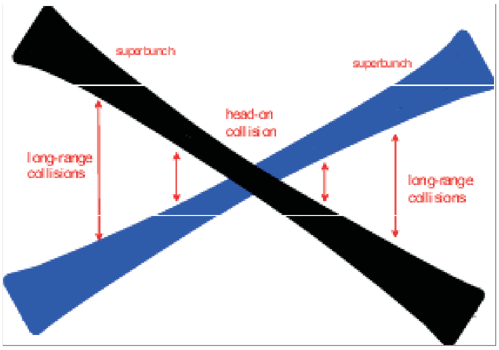

Fig. 4. Schematic of a super-bunch collision, consisting of 'head-on' and 'long-range' components

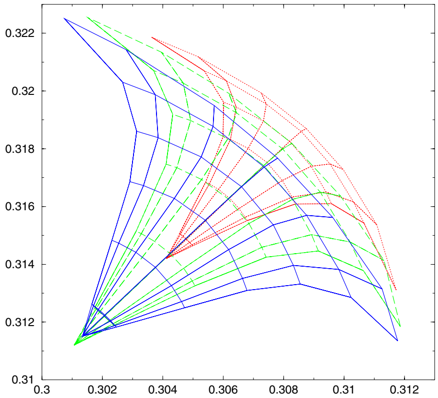

Fig. 5. Comparison of beam-beam tune footprints for regular bunches, corresponding to betatron amplitudes extending from 0 to $6\,\sigma$, for LHC nominal (*dotted, red line*), ultimate (*dashed, green line*), and large Piwinski parameter configuration (*solid, blue line*) with two interaction points and alternating horizontal-vertical crossing planes (see Table 2). (Courtesy H. Grote)

Note that the peak luminosity is proportional to beam energy and normalized transverse emittance. By increasing the injection energy it is possible to store a beam with larger normalized emittance and the same transverse size at injection, corresponding to more intensity and more luminosity at the beam-beam limit. The beam size in collision increases and the relative beam separation decreases, leading to a reduction of the diffusive aperture unless long range beam-beam effects can be compensated.

Another possibility to achieve significant luminosities with large crossing angles consists in colliding very long 'super-bunches', as discussed in [12] and shown in Fig. 4. A few super-bunches with flat longitudinal distribution yield

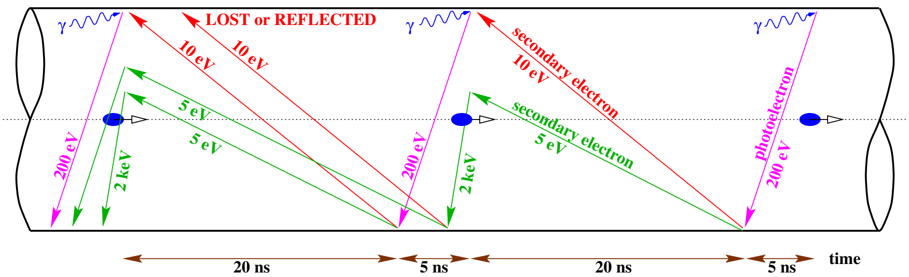

Fig. 6. In the LHC, photoelectrons created at the vacuum pipe wall are accelerated by proton bunches up to 200 eV and cross the pipe in about 5 ns. Slow or *reflected* secondary electrons survive until the next bunch. Depending on vacuum pipe surface conditions (SEY) and bunch spacing, this may lead to an electron cloud build-up with implications for beam stability, emittance growth, and heat load on the cold LHC beam screen

Table 1. Possible scenarios with 75 ns and 25 ns bunch spacing for an early LHC luminosity run at 7 TeV with integrated luminosity of about 10 fb^{-1} in 200 fills, assuming an average physics run time $T_{\mathrm{run}} = 14$ h and $T_{\mathrm{turnaround}} = 10$ h

Parameter	Units	75 ns spacing	25 ns spacing	nominal
number of bunches	n_{b}	936	2808	2808
protons per bunch	N_{b} $[10^{11}]$	0.9	0.4	1.15
aver. beam current	I_{av} [A]	0.15	0.20	0.58
norm. tr. emittance	ε_{n} [μm]	3.75	3.75	3.75
r.m.s. bunch length	σ_{s} [cm]	7.55	7.55	7.55
r.m.s. energy spread	σ_{E} $[10^{-4}]$	1.13	1.13	1.13
IBS growth time	τ_x^{IBS} [h]	135	304	106
beta at IP1-IP5	β^* [m]	1.0	0.55	0.55
full crossing angle	θ_{c} [μrad]	250	285	285
diffusive aperture	d_{da}/σ	10.0	7.5	6.2
luminosity lifetime	τ_{L} [h]	22	26	15
peak luminosity	L $[10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}]$	0.12	0.12	1.0
events/crossing		7.1	2.3	19.2
lumi over 200 fills	L_{int} $[\mathrm{fb}^{-1}]$	9.3	9.5	66.2

a luminosity $\sqrt{2}$ times higher than many short Gaussian bunches with the same beam-beam tune shift and identical bunch population [13].

3.2 Minimum crossing angle

An approximate scaling law for the so-called 'diffusive aperture' d_{da} with long range beam-beam encounters is $(d_{\mathrm{sep}} - d_{\mathrm{da}})/\sigma \propto \sqrt{k_{\mathrm{par}}\, N_{\mathrm{b}}/\varepsilon_{\mathrm{n}}}$, where $d_{\mathrm{sep}}/\sigma \simeq \theta_{\mathrm{c}}/\sigma_\theta$ is the relative beam separation (in units of the r.m.s. transverse beam size σ) at the k_{par} parasitic encounters, and $\sigma_\theta = \sqrt{\varepsilon/\beta^*}$ the r.m.s. angular beam divergence at the IP. Note that the ratio $(d_{\mathrm{sep}} - d_{\mathrm{da}})/\sigma$ is independent of the betatron function and the beam energy; it is again a function of the brilliance $N_{\mathrm{b}}/\varepsilon_{\mathrm{n}}$. Combining this scaling law with particle tracking results [14,15], the diffusive aperture is given by the empirical expression

$$d_{\mathrm{da}}/\sigma \simeq \theta_{\mathrm{c}}\, \sqrt{\beta^*/\varepsilon} - 3\, \sqrt{\frac{k_{\mathrm{par}}}{2 \times 32}\, \frac{N_{\mathrm{b}}}{10^{11}}\, \frac{3.75\, \mu\mathrm{m}}{\varepsilon_{\mathrm{n}}}} .$$

With nominal LHC crossing angle $\theta_{\mathrm{c}} = 300\, \mu$rad and r.m.s. angular beam divergence $\sigma_\theta = 31.7\, \mu$rad, the beam separation is $d_{\mathrm{sep}} \simeq 9.5\, \sigma$. The diffusive aperture $d_{\mathrm{da}} \simeq 6 \div 6.5\, \sigma$ for nominal beam parameters and separation scheme, with $k_{\mathrm{par}} = 2 \times 32$ parasitic encounters around the two high luminosity experiments, corresponds to a reduction by more than $3\, \sigma$. Preserving a comparable dynamic aperture in collision with higher bunch intensities requires larger crossing angles.

Nominal and ultimate LHC parameters at 7 TeV are presented in Table 2, together with a possible operation scenario with high brilliance and large 'Piwinski parameter' $\theta_{\mathrm{c}} \sigma_z/\sigma^*$. The corresponding beam-beam tune footprints are shown in Fig. 5. A crossing angle of 345 μrad requires a challenging orbit control during β-squeeze and may not be compatible with the foreseen installation of beam screens in the triplet magnets, resulting in a reduction of the available mechanical aperture.

3.3 Electron cloud effects

The mechanism of the possible build-up of an electron cloud in the LHC vacuum chamber is sketched in Fig. 6. The electron cloud may induce beam instabilities and

Table 2. Nominal and ultimate LHC parameters at 7 TeV. The last column refers to operation with large ‘Piwinski parameter’. The corresponding beam-beam tune footprints are compared in Fig. 5

parameter	symbol	units	nominal	ultimate	Piwinski
number of bunches	n_b		2808	2808	2808
bunch spacing	Δt_sep	ns	25	25	25
protons per bunch	N_b	10^{11}	1.1	1.7	2.6
aver. beam current	I_av	A	0.56	0.86	1.32
norm. tr. emittance	ε_n	μm	3.75	3.75	3.75
long. emittance	ε_L	eV s	2.5	2.5	4.0
peak RF voltage	V_RF	MV	16	16	3/1
RF frequency	f_RF	MHz	400.8	400.8	200.4/400.8
r.m.s. bunch length	σ_z	cm	7.55	7.55	15.2
r.m.s. energy spread	σ_E	10^{-4}	1.13	1.13	0.9
IBS growth time	$\tau_{x,\mathrm{IBS}}$	h	111	72	87
beta at IP1-IP5	β^*	m	0.5	0.5	0.5
full crossing angle	θ_c	μrad	300	315	345
Piwinski parameter	$\theta_\mathrm{c}\sigma_z/\sigma^*$		1.43	1.50	3.29
lumi at IP1-IP5	L	$10^{34}/\mathrm{cm}^2\,\mathrm{s}$	1.0	2.3	3.6

emittance dilution, as well as heat deposition in the cold arcs of the machine.

The corresponding average arc heat load as a function of the bunch population is shown in Fig. 7 for the nominal bunch spacing of 25 ns and compared to the cooling capacity of the beam screen. A higher heat load is expected for shorter bunch spacings, as depicted in Fig. 8

A great potential advantage of operation with long super-bunches is to drastically reduce the cryogenic heat load induced by the electron cloud, as sketched in Fig. 9 and demonstrated in Fig. 10. However the associated RF manipulations and beam parameters are challenging and require further studies. To keep the pile-up in the experimental detectors down to a reasonable level, the minimum number of super-bunches is estimated to be around 100.

4 LHC upgrade scenarios

We consider the following three phases for the LHC upgrade:

- LHC Phase 0: maximum performance without hardware changes,
- LHC Phase 1: maximum performance keeping the LHC arcs unchanged,
- LHC Phase 2: maximum performance with ‘major’ hardware changes.

The nominal LHC performance at 7 TeV corresponds to a total beam-beam tune spread of 0.01, with a luminosity of $10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ in IP1 and IP5 (ATLAS and CMS), halo collisions in IP2 (ALICE) and low-luminosity in IP8 (LHC-b). The steps to reach ultimate performance without hardware changes are shown in Table 3. The ultimate dipole field of 9 T corresponds to a beam current limited by cryogenics and/or by beam dump considerations.

5 LHC Phase 1: Luminosity upgrade

Possible steps to increase the LHC luminosity with hardware changes only in the LHC insertions and/or in the injector complex include the baseline scheme shown in Table 4. Step 4 is not cheap since it requires a new RF system with 43 MV at 1.2 GHz and a power of about 11 MW/beam (estimated cost 56 MCHF). The changeover

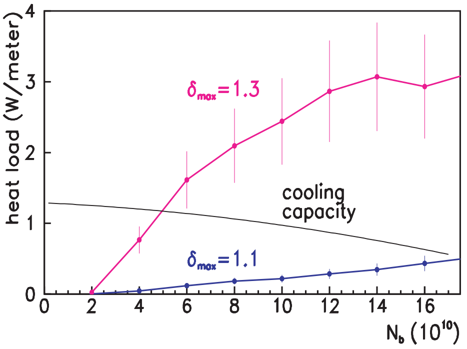

Fig. 7. Average arc heat load due to electron cloud and LHC cooling capacity as a function of bunch population N_b, for 25 ns bunch spacing and two different values of the maximum secondary emission yield δ_max. Elastically reflected electrons are included [16]

from 400 to 1200 MHz is assumed at 7 TeV, or possibly at an intermediate flat top, where stability problems may arise in view of the reduced longitudinal emittance of 1.78 eVs. The horizontal Intra-Beam Scattering growth time decreases by about $\sqrt{2}$, as shown in Table 5.

With a *reduced bunch spacing* of 15 ns (respectively 12.5 ns) and *ultimate bunch intensity*, one would be able to reach a luminosity of $7.7 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ (respectively $9.2 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$). However electron cloud effects are expected to severely limit the bunch intensity for a bunch spacing shorter than 25 ns. Moreover, an increased number of long range beam-beam encounters leads to a further reduction of dynamic aperture and to an increased tune footprint, unless beam-beam compensation schemes are successfully implemented or the crossing angle is further increased. Therefore the maximum luminosity with the baseline scheme will presumably never exceed $6 \div 7 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. In the baseline scheme, operation with bunched beams and large crossing angles of several mrad, to pass each beam through separate final quadrupoles of reduced aperture, would require crab cavities to avoid a severe luminosity loss.

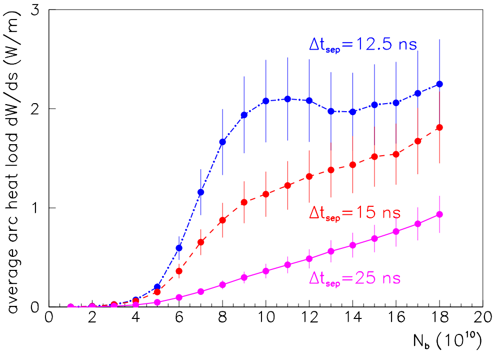

Fig. 8. Average arc heat load as a function of bunch population for bunch spacings of 12.5 ns, 15 ns, and 25 ns, and a maximum secondary emission yield $\delta_{\max} = 1.1$. Elastically reflected electrons are included

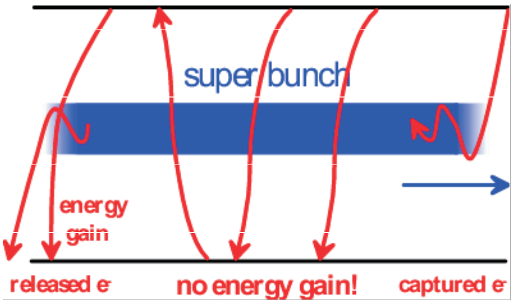

Fig. 9. Schematic of reduced electron cloud build-up for a super-bunch (courtesy F. Zimmermann)

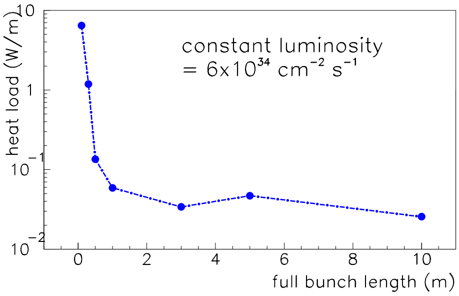

Fig. 10. Simulated heat load in an LHC arc dipole due to the electron cloud as a function of super-bunch length for $\delta_{\max} = 1.4$, considering a constant flat top proton line density of $8 \times 10^{11}\,\mathrm{m}^{-1}$ with 10% linearly rising and falling edges. The number of bunches is varied so as to keep the luminosity constant and equal to $6 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$

Table 3. Steps for the LHC upgrade to ultimate performance: collisions in ATLAS and CMS only, with alternating horizontal-vertical crossing planes

1. collide beams only in IP1 and IP5 → $\beta^* = 0.5\,\mathrm{m}$
2. increase crossing angle to $\theta_c = 315\,\mu\mathrm{rad}$
3. increase N_b up to the beam-beam limit → $L = 2.3 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
4. optionally increase the dipole field to 9 T (ultimate field) → $E_{\max} = 7.54\,\mathrm{TeV}$

Table 4. Baseline scheme for an LHC luminosity upgrade: collisions in ATLAS and CMS only, with alternating horizontal-vertical crossing planes

1. modify insertion quadrupoles and/or layout → $\beta^* = 0.25\,\mathrm{m}$
2. increase crossing angle by $\sqrt{2}$ → $\theta_c = 445\,\mu\mathrm{rad}$
3. increase N_b up to ultimate intensity → $L = 3.3 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
4. halve σ_z with high harmonic RF system → $L = 4.6 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
5. double number of bunches (and increase θ_c!) → $L = 9.2 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ excluded by electron cloud?

If the single bunch population can be increased above the ultimate intensity, keeping the same nominal transverse emittance, operation with large Piwinski parameter allows us to reach a luminosity of $7.2 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ with nominal bunch length and nominal bunch spacing. Other parameters are shown in Table 5.

5.1 Triplet aperture requirements: Baseline scheme

The aperture of the triplet magnets must provide enough space to enclose $9\,\sigma$ of beam envelope per beam, a beam separation of $7.5\,\sigma$, peak orbit excursions of 3 mm, mechanical tolerances of 1.6 mm, a β-beating of 20% and a spurious dispersion orbit of up to 4 mm, yielding an approximate requirement for the triplet diameter D_{trip}

$$D_{\mathrm{trip}} > 1.1 \times (7.5 + 2 \times 9) \cdot \sigma + 2 \times 8.6\,\mathrm{mm}. \qquad (1)$$

The nominal normalised beam emittance is $\varepsilon_n = 3.75\,\mu\mathrm{m}$ and the beam size inside the triplet magnets becomes

$$\sigma = \sqrt{\beta \frac{\varepsilon_n}{\gamma}}. \qquad (2)$$

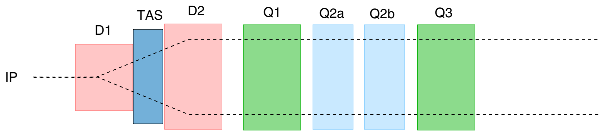

Fig. 11. Sketch of a possible IR layout for an LHC luminosity upgrade with separation dipoles close to the IP and separated magnet bores inside the triplet magnets (courtesy O. Brüning)

For the nominal optics configuration with $\beta^* = 0.5\,\mathrm{m}$ one obtains a maximum beam size of $\sigma = 1.54\,\mathrm{mm}$ and the triplet diameter must satisfy

$$D_{\mathrm{trip}}(\beta^* = 0.5\,\mathrm{m}) > 60.4\,\mathrm{mm} \tag{3}$$

which is compatible with the current triplet aperture of 60 mm. It should be noted here that the above calculation provides only an approximate estimate for the required magnet aperture which is sufficient for the comparison of different triplet layouts. A precise calculation of the required magnet aperture is based on two-dimensional tracking of the beam halo around the machine. Furthermore it should be underlined that most of the long range beam-beam interactions occur in the drift space between the triplet quadrupole magnets left and right from the IP where the minimum beam separation is much larger than the $7.5\,\sigma$ quoted above (approximately $9.5\,\sigma$).

For an optics configuration with $\beta^* = 0.25\,\mathrm{m}$ one obtains a maximum beam size of $\sigma = 2.185\,\mathrm{mm}$ and the triplet diameter must satisfy

$$D_{\mathrm{trip}}(\beta^* = 0.25\,\mathrm{m}) > 78.5\,\mathrm{mm} \tag{4}$$

which is no longer compatible with the current specification of the triplet aperture of 60 mm.

5.2 Alternative IR layout for LHC Phase 1

A possible alternative IR layout for $\beta^* = 0.25\,\mathrm{m}$ with separation dipoles close to the IP is sketched in Fig. 11. Its main advantages are a reduced number of long range beam-beam interactions and no crossing-angle bump inside the triplet magnets, *i.e.*, no feed-down errors. The corresponding magnet requirements are shown in Table 6. Other alternative IR layouts are discussed in [18].

6 LHC Phase 2: Luminosity and energy upgrade

Possible steps to increase the LHC performance with 'major' hardware changes in the LHC arcs and/or in the injectors include:

- Modify the injectors to significantly increase the beam intensity and brilliance beyond its ultimate value, possibly in conjunction with beam-beam compensation schemes, *e.g.*, by means of pulsed electromagnetic lenses [17].
- Equip the SPS with superconducting magnets, upgrade transfer lines, and inject into the LHC at 1 TeV. For given mechanic and dynamic apertures at injection, this option can increase the LHC luminosity by nearly a factor two, at constant beam-beam parameter $N_{\mathrm{b}}/\varepsilon_{\mathrm{n}}$, in conjunction with long range beam-beam compensation schemes. This would also be the natural first step in view of an LHC energy upgrade, since the energy swing would be reduced by a factor 2. An interesting alternative is a cheap, compact low-field booster ring to be installed in the LHC tunnel.
- Install new dipoles with a field of 15 T and a safety margin of about 2 T, which are considered a reasonable target for 2015 and could be operated by 2020 (see Fig. 12). This would allow us to reach a beam energy around 12.5 TeV.

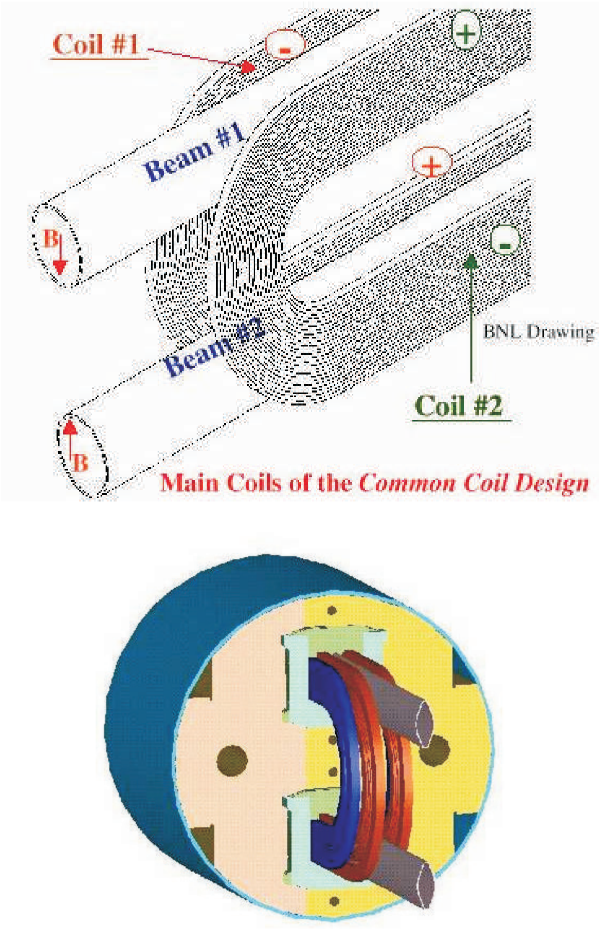

Fig. 12. Sketch of the Common Coil design for a double aperture dipole magnet. The coils couple the two apertures and can be flat (no difficult ends). One of the most difficult challenges will be to make it at reasonable cost, less than 5 kEuro/(double)T.m say, including cryogenics, to be compared with about 4.5 kEuro/(double)T.m for the present LHC

Table 5. List of LHC parameters at 7 TeV corresponding to possible luminosity upgrade scenarios with reduced β^*. The last column refers to one or several flat super-bunches, with a total length of about 260 m, confined by barrier buckets

parameter	symbol	units	baseline	Piwinski	super-bunch
number of bunches	n_b		2808	2808	1
bunch spacing	Δt_sep	ns	25	25	
protons per bunch	N_b	10^{11}	1.7	2.6	5600
aver. beam current	I_av	A	0.86	1.32	1.0
norm. tr. emittance	ε_n	μm	3.75	3.75	3.75
long. emittance	ε_L	eV s	1.78	2.5	15000
peak RF voltage	V_RF	MV	43	16	3.4
RF frequency	f_RF	MHz	1202.4	400.8	10
r.m.s. bunch length	σ_z	cm	3.78	7.55	7500
r.m.s. energy spread	σ_E	10^{-4}	1.60	1.13	5.8
IBS growth time	$\tau_{x,\mathrm{IBS}}$	h	42	46	63
beta at IP1-IP5	β^*	m	0.25	0.25	0.25
full crossing angle	θ_c	μrad	445	485	1000
diffusive aperture	d_da	σ	6.0	6.0	6.0
Piwinski parameter	$\theta_\mathrm{c}\sigma_z/\sigma^*$		1.50	3.27	
lumi at IP1-IP5	L	$10^{34}/\mathrm{cm}^2\,\mathrm{s}$	4.6	7.2	9.0

Table 6. Tentative magnet parameters for a triplet layout with separated beams inside the triplet magnets. The beam separation does not include the additional separation from the crossing angle bump. We assume that the beam separation can be done via two 11.4 m long 15 T dipole magnets (possibly with high temperature superconducting coils)

magnet	type	length	diameter range	beam separation	strength
D1	1 aperture	11.4 m	34 mm ↔ 131 mm	0 ↔ 84 mm	15 T
D2	2-in-1	11.4 m	50 mm ↔ 60 mm	110 mm ↔ 194 mm	15 T
Q1	2-in-1	4.5 m	60 mm ↔ 70 mm	194 mm	230 T/m
Q2	2-in-1	2 × 4.5 m	70 mm ↔ 78 mm	194 mm	257 T/m
Q3	2-in-1	5.0 m	70 mm ↔ 78 mm	194 mm	280 T/m

7 Recommendations for future studies and R&D

Reaching the nominal LHC performance is a challenging task. The emittance budget through the injector chain is tight and we have to learn how to overcome electron cloud effects, inject into the LHC ring, accelerate and collide almost 6000 high intensity proton bunches, protect superconducting magnets and physics detectors by an adequate collimation system, safely dump the beams, etc. Attaining or exceeding the ultimate LHC performance will be even more challenging. Further accelerator physics studies in view of a luminosity upgrade, *e.g.*, by optimizing machine operation near the beam-beam limit, will be directly applicable also to reach nominal machine performance, *e.g.*, with fewer bunches of higher intensity. Similarly, investigating and overcoming intensity limitations in the LHC and its injectors is essential for a fast and effective reduction of electron cloud effects by beam scrubbing.

The radiation damage limit for the IR quadrupoles ($\sim$ 700 fb^{-1}) may already be reached by 2013. New triplet quadrupoles with high gradient and larger aperture, and/or alternative IR layouts, are needed for the LHC Phase 1 luminosity upgrade with reduced β^*. Increasing the quadrupole aperture has the additional advantage of letting through radiation. Further studies are necessary to specify field quality of IR magnets, required upgrades of beam instrumentation, collimation and machine protection. To reduce the collimator impedance during β-squeeze and physics conditions, the new triplet aperture should be i) large and ii) possibly protected by local tertiary collimators.

Upgrades in beam intensity and brilliance are a viable option for a staged increase of the LHC luminosity. A possibility being considered also for CERN-Neutrino-to-Gran-Sasso beams is to upgrade the proton linac from 50 to 120 ÷ 160 MeV, to overcome space charge limitations at injection in the booster. Then the ultimate LHC intensity would become easy to achieve and a further 30% increase would be possible with almost the same emittance and the same machine filling time. This requires R&D for cryogenics, vacuum, RF, beam dump, radiation issues, and injectors, and operation with large crossing angles. Experimental studies on electron cloud (e.g. beam scrubbing in cold conditions), long range, and strong-strong beam-beam effects are important, as well as machine experiments in existing hadron colliders with large Piwinski parameter and many (flat) bunches. A strong international collaboration (US-LARP, ESGARD) is welcome/needed for LHC machine studies and commissioning. Beam-beam compensation schemes, *e.g.* with pulsed wires, can reduce tune footprints and loss of dynamic aperture due to long range collisions. They need experimental validations.

Interesting possibilities currently under study to pass each beam through separate final quadrupoles include alternative beam separation schemes with separation dipoles in front of the triplet quadrupoles and collision of long super-bunches with very large θ_c. With a crossing angle of a few mrad, one or several super-bunches with a total length of about 300 m and a total beam intensity $I_{\text{beam}} = 1\,\text{A}$ in each LHC ring would be compatible with the beam-beam limit. The corresponding luminosity in ATLAS and CMS (with alternating H-V crossings) would be $9 \times 10^{34}\,\text{cm}^{-2}\ \text{s}^{-1}$. Further studies are needed to compare advantages and disadvantages of long super-bunches versus conventional bunched beams and to finalize the Interaction Region layout.

8 Conclusions

The super-bunch option is interesting for large crossing angles, can potentially avoid electron cloud effects and minimize the cryogenic heat load. One could inject a bunched beam, accelerate it to 7 TeV, and then use barrier buckets to form 100 or more 10 ns long super-bunches to reduce the pile-up noise in the experiments.

A major and sustained R&D effort on new superconducting materials and magnet design is needed for any LHC performance upgrade. This requires an international collaboration: new low-β quadrupoles with high gradient and larger aperture based on Nb_3Sn superconductor require 9-10 years for short model R&D and component development, prototyping, and final production.

An increased injection energy into the LHC, in conjunction with long range beam-beam compensation schemes, would yield a proportional luminosity gain. A pulsed Super-SPS and new superconducting transfer lines could also be the first step for an LHC energy upgrade. An interesting alternative to increase the injection energy into the LHC (or Super-LHC) is to use the present SPS as injector and introduce cheap, compact low field booster rings in the LHC tunnel. Dipole magnets with a nominal field of 15 T can be considered a reasonable target for 2015. This would allow us to reach a proton beam energy around 12.5 TeV in the LHC tunnel, but requires a vigorous R&D programme on new superconducting materials.

Acknowledgements. I would like to thank L. Evans and S. Myers for launching the LHC Upgrade feasibility study and all the colleagues who have contributed to the CERN task force. This paper includes some results of further discussions with W. Herr and F. Zimmermann on Pacman and super-bunches, and with O. Brüning and J. Strait on alternative IR layouts and radiation damage limit for the IR magnets. Finally, I would like to thank Prof. L. Foà for a careful reading of the manuscript.

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